AN EVALUATION OF PROPERTIES FOR CALIFORNIA REFORMULATED GASOLINE

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ABSTRACT

California began using a cleaner-burning reformulated gasoline in March 1996. The California reformulated gasoline regulations limit eight specific properties, with flexibility given to refiners to average properties, or to use a predictive model to blend gasolines having equivalent emission benefits. Data were collected from refiners, compliance fuel sample monitoring, and the California Energy Commission. These data are used to compile a picture of California reformulated gasoline's average properties and the range of properties. The properties evaluated include sulfur, aromatic hydrocarbon, benzene, olefin, and oxygen content, distillation temperatures at 50 and 90 percent volume, and Reid vapor pressure. Additionally, data have been collected pertaining to the energy density which affects the fuel economy of this cleaner-burning gasoline. This evaluation confirms the Air Resources Board's pre-regulation analysis on emission performance and fuel economy.

INTRODUCTION

Presented is an evaluation of data which illustrates the present composition of gasoline in California. California introduced a cleaner-burning reformulated gasoline (CaRFG) in 1996 as part of its comprehensive program to reduce air pollution. Since CaRFG's introduction, the Air Resources Board (ARB) has monitored the composition of gasoline sold in California through several mechanisms. An evaluation of this data was performed to verify that estimated emission benefits are being met. The ARB also calculated the energy difference of CaRFG on a subset of available data using oxygen content, specific gravity, distillation temperatures at 10, 50 and 90 percent volume (T10, T50 and T90), and aromatic hydrocarbon content.

BACKGROUND

Air Quality Compared to California Phase 1 gasoline (Post-1992), CaRFG reduces emissions of volatile organic compounds (VOC), oxides of nitrogen (NOX), and carbon monoxide (CO), as well as the risk from exposure to toxic air contaminants. Table 1 shows the emission reductions attributable to CaRFG.

CaRFG Regulation The CaRFG regulations set specifications for eight properties with several compliance options available to gasoline producers. Compliance options which provide refiners flexibility in meeting the regulation include; (1) compliance with regulation flat limits, (2) the use of averaging based on the regulation averaging limits; (3) the use of a predictive model; or (4) the use of an alternative formulation certified to have equivalent emission performance. Since the implementation of the CaRFG regulation, no fuel producers have used the alternative formulation method of compliance.

The CaRFG regulation sets cap limits for each of the eight regulated properties. The cap limits ensure that compliance can be demonstrated at all points of the distribution and marketing system. These limits are listed in Table 2.

Regulation Flat limits The regulation flat limits, listed in Table 2, are fixed for each regulated property and cannot be exceeded when complying by this method. Refiners are not required to report batch properties to the ARB when using this method of compliance.

Averaging Limits The averaging limits are listed in Table 2. Gasoline producers using the averaging limits to comply with the CaRFG must demonstrate that volume weighted gasoline production averages meet each specification limit by the end of the averaging period without exceeding the cap limit. As shown in Table 2, the averaging limits are lower than the flat limits. Under this compliance option refiners must report the measured properties and volumes of each batch of fuel produced to the ARB.

Predictive Model The Predictive Model provides fuel producers with flexibility to optimize the gasoline properties of fuel produced to match the capabilities of their facilities. The predictive model allows fuel producers to designate alternative flat limits and averaging limits while maintaining the emission benefits of the CaRFG regulation. The majority of producers have chosen to use this method of compliance. The compliance reporting requirements are similar to the compliance options described above. However, the specifications of the eight regulated properties must be reported to the ARB.

DATA COLLECTED

Regulation Flat Limits Since no reporting by fuel producers to the ARB is required for this option, it was assumed that fuel producers using this option produced fuel with properties at the regulation flat limits. The gasoline production volume was obtained from the California Energy Commission (CEC) from weekly production data.

Regulation or Predictive Model Averaging Limits Under this option, gasoline producers must report the properties and volume of each batch produced to the ARB; thus, the average properties were calculated directly from their compliance reports.

Predictive Model Flat Limits Many gasoline producers used several predictive model formulations in a given month. Since the volume of gasoline produced under each formulation was not reported, a typical formulation reported from each producer in a given month was used. The production volume for each producer was again estimated with CEC weekly gasoline production data.

Compliance Sample Data ARB compliance sampling data were used to evaluate energy density changes associated with CaRFG. A total of 103 samples comprised this subset of CaRFG data.

Presented Data

Table 3 lists the approximate volume weighted average properties of the gasoline being produced in California from March 1996 through September 1996.

Table 4 summarizes the properties found in samples of summertime CaRFG sold in 1996. The table also summarizes and provides a comparison to summertime California gasoline sold in 1990 and 1991.

DATA ANALYSIS

Evaluation CaRFG Regulatory Compliance Table 3 shows that the average CaRFG properties of fuel sold in California are very similar to the regulation flat limits. Of the eight properties, only the T90 specification is higher. It is higher because many fuel producers have been able to increase the T90 when meeting the predictive model flat limits.

Evaluation of Emissions Effects The predictive model provides the basis for the emissions characteristics of the formulations presented here. The predictive model predicts the relative change in emissions compared to the regulation flat limits or averaging limits. Although changes in emissions compared to changes in properties are not always linear, they can be estimated linearly for the range of properties allowed in the regulation. Because of this, the average emissions of each batch are expected to be similar to the emissions of the average properties of all batches.

The in-use California average gasoline properties have the same emissions benefits as anticipated by the ARB. Since the averaging limits are more stringent than the flat limits, the average properties of the in-use gasolines meeting averaging limit specifications were evaluated separately from those meeting flat limit specifications. Table 3 lists the average gasoline properties from March to September 1996 for gasoline meeting the flat limits, averaging limits, and the overall average gasoline properties.

Evaluation of Fuel Economy Effects All of the eight CaRFG property limits may have some impact on volumetric energy content (Btu/gal) and vehicle fuel economy (mpg). Vehicle fuel economy has been shown to correlate well with gasoline energy content as estimated by ASTM D 3338, modified by considering oxygenated contents separately (Hochhauser, et al, 1993). The most significant of the regulated properties to this procedure are oxygen content, aromatic hydrocarbon content, T50 and T90. The sulfur content has an insignificant impact at the levels found in CaRFG, and is not considered in our estimation of the energy contents of CaRFG.

The oxygen content requirement decreases energy content, because the oxygenated compounds have reduced lower heating values (Btu/lbm) than gasoline. Gasoline with 2 percent by weight oxygen has about a 2 percent lower volumetric energy content than non-oxygenated gasoline. The specific gravity is second only to the oxygen content in its significance to the energy content of CaRFG. Specific gravity is not a regulated property; however, all of the eight regulated properties may have some impact on the specific gravity. The reduction of Reid vapor pressure required of summertime CaRFG may be the only property regulation which tends to increase specific gravity and, consequently, energy content and fuel economy. Aromatic hydrocarbon content, T50 and T90 limits tend to decrease specific gravity, energy content, and fuel economy. The difference in the mean energy contents of CaRFG and Pre-CaRFG is shown in Table 4 to be -3.5 percent.

Consider a vehicle and engine operating at steady speed and load at a given excess-air factor (air-to-fuel ratio relative to theoretical). Ignore changes in thermal efficiency due to small changes in air, fuel, and exhaust flow, which are required to maintain the fixed conditions. Then, a small relative change in fuel energy content should result in an equivalent relative change in vehicle fuel economy (Blackmore and Thomas, 1977). Compared to a fuel with 3 percent greater energy content, under the same conditions the vehicle will travel a 3 percent shorter distance burning the same volume of lower energy fuel. Under the assumptions, a decrease in specific gravity and increase in oxygen content, such as from CaRFG regulations, do not change this relationship. However, under transient operation of the vehicle and engine, or with carburetion designed to maintain a fixed air-to-fuel ratio, the CaRFG regulations should result in reduced fuel mass flow and enleanment (excess-air factor increase) (API, 1988). A slight increase in fuel volume flow should have a negative effect on vehicle fuel economy. Enleanment could increase or decrease engine thermal efficiency; the decrease occurring only with enleanment beyond an excess-air factor of about 1.1 (Adler, 1986).

The change in thermal efficiency should have a corresponding effect on vehicle fuel economy. This theory suggests that the relative change in vehicle fuel economy is proportional and roughly equivalent to the relative change in gasoline energy content under normal operation of most vehicles. Laboratory dynamometer testing of vehicles operated over the Federal Test Procedure cycle confirms this theory and suggests that the constant proportionality is less than one (Hochhauser, et al, 1993). We conclude that the percent change in average fuel economy of California's gasoline-fueled vehicles, due to the introduction of CaRFG, is less than the percent change in the average energy content of gasoline.

CONCLUSIONS

Our evaluation of CaRFG data shows that fuel producers have met the regulation property limits and that they have made use of available regulation flexibility by implementing various compliance options. Based on analysis performed on the average properties presented, it appears that emission benefits predicted for the regulation are being realized. Additionally, based on sample data and energy density calculations, the effect on fuel economy is relatively small. The overall evaluation of the data confirms pre-regulation analysis of emissions and fuel economy effects.

TABLE 1
Predicted Emission Benefits of California Reformulated Gasoline

Market Segment Reductions	VOC	NOx	CO
On-Road	17%	11%	11%
Off-Road	10%	--	--
Marketing Operations	7%	--	--
Total	**15%**	**11%**	**11%**

Note: Emission benefits of CaRFG for off-road and marketing operations are not separated from on-road categories.

TABLE 2
California Reformulated Gasoline Specification Limits

Property	Flat Limits	Averaging Limits	Cap Limits
Aromatic Hydrocarbon, vol%	25	22	30
Benzene, vol%	1.0	0.80	1.2
T50, F	210	200	220
T90, F	300	290	330
Olefins, vol%	6.0	4.0	10.0
RVP, psi	7.0	--	7.0
Sulfur, ppmw	40	30	80
Oxygen, vol%	1.8 to 2.2	--	1.8 to 2.7

TABLE 3
California Average Gasoline Properties
(March to September 1996)

Property	Flat Limits	Averaging Limits	Overall
Aromatic Hydrocarbon, vol%	24.5	23.9	24.2
Benzene, vol%	0.87	0.55	0.73
T50, F	204	200	202
T90, F	313	298	306
Olefins, vol%	6.6	3.6	5.2
RVP, psi	7.0	7.0	7.0
Sulfur, ppmw	41	14	29
Oxygen, vol%	2.0	1.8	1.9

TABLE 4
Evaluation of Fuel Economy Effects of CaRFG

	Oxygen (%wt)	AroHC (%vol)	RVP (psia)	T10 (F)	T50 (F)	T90 (F)	Sp.Grav. @ 60F	ASTM D 3338 (Btu/gal)
CaRFG (103 Samples)								
Minimum	1.30	9.5	5.96	139	162	276	0.7241	110,200
Maximum	2.90	31.6	7.19	158	229	339	0.7522	113,000
Median	2.17	22.9	6.73	144	201	308	0.7407	111,800
Mean	2.18	22.4	6.71	145	201	309	0.7400	111,700
Pre-CaRFG (90-91) (441 Samples)								
Minimum	Not Known, But Small	4.5	6.9	98	170	281	0.706	109,900
Maximum		60.8	9.3	156	251	362	0.795	120,300
Median		35.8	8.5	130	222	331	0.757	115,800
Mean		36.1	8.4	131	221	329	0.758	115,800
Difference of Means	+2	-13.7	-1.7	+14	-20	-20	-2.4%	-3.5%

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